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## A non-PRE double-peaked burst with oscillations: burning front propagation and stalling

Sudip Bhattacharyya<sup>1,2</sup>, and Tod E. Strohmayer<sup>2</sup>

### ABSTRACT

Non-photospheric-radius-expansion (non-PRE) double-peaked bursts may be explained in terms of spreading (and temporary stalling) of thermonuclear flames from a rotational pole on the neutron star surface, as we argued in a previous study. Here we analyze Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) data of such a burst from the low mass X-ray binary (LMXB) system 4U 1636–536, and show that our model (with ignition at high latitudes) can qualitatively explain the observed burst profile, and spectral evolution. Moreover, the evolution of the source radius inferred from the data shows a strong signature of temporary stalling of the burning front, which is an essential ingredient of our model. This implies that an understanding of thermonuclear flame spreading on neutron stars can be achieved by a simultaneous study of the evolution of intensity and spectrum of these bursts. We also report the discovery of millisecond period brightness oscillations from this burst, which is the first such observation from a non-PRE double-peaked burst. Our model can explain the corresponding oscillation amplitude during the first (weaker) peak, and the absence of oscillations during the second peak. We discuss how observations of oscillations during non-PRE double-peaked bursts provide an additional tool for understanding thermonuclear flame spreading successfully.

*Subject headings:* accretion, accretion disks — relativity — stars: neutron — X-rays: binaries — X-rays: bursts — X-rays: individual (4U 1636–536)

### 1. Introduction

Thermonuclear burning of matter accumulated on the surfaces of accreting neutron stars produces type I X-ray bursts (Grindlay et al. 1976; Belian, Conner, & Evans 1976;

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<sup>1</sup>Department of Astronomy, University of Maryland at College Park, College Park, MD 20742-2421

<sup>2</sup>X-ray Astrophysics Lab, Exploration of the Universe Division, NASA's Goddard Space Flight Center, Greenbelt, MD 20771; sudip@milkyway.gsfc.nasa.gov, stroh@clarence.gsfc.nasa.gov

Woosley, & Taam 1976, Joss 1977; Lamb, & Lamb 1978). Although the lightcurves of most of these bursts have single-peaked structures, some of the strongest bursts from a given source show double-peaked profiles in higher energy bands. These can be explained in terms of photospheric radius expansion (PRE; due to radiation pressure), and subsequent contraction (Paczynski 1983; Ebisuzaki, Hanawa, & Sugimoto 1984; Lewin et al. 1976; Hoffman, Cominsky, & Lewin 1980; Smale 2001). However, double-peaked structures are also seen in weak non-PRE bursts, and in such cases, these structures appear both in low and high energy bands. Such bursts have so far only been observed infrequently from a few sources (Sztajno et al. 1985; Melia, & Zylstra 1992). Until recently, the proposed models for these bursts could not simultaneously explain their intensity profiles, spectral evolution, X-ray emission area increase, and rarity (Fujimoto et al. 1988; Fisker, Thielemann, & Wiescher 2004; Regev, & Livio 1984; Melia, & Zylstra 1992). However, the recent model of Bhattacharyya & Strohmayer (2005a), based on thermonuclear flame spreading on neutron stars, can qualitatively explain these properties. According to this model, such bursts are ignited very close to a rotational pole, and then the burning front propagates (as a more or less  $\phi$ -symmetric belt) towards the equator. Near-polar ignition is required to understand double-peaked bursts that do not show any millisecond period brightness oscillations. As the front approaches the equator, it stalls for a few seconds before speeding up again into the opposite hemisphere. The stalling of the front allows the burning region to cool, and the luminosity to decrease. After a few seconds, as the flame starts spreading again, the increased emission area causes the luminosity to increase again, and hence a double-peaked structure appears in the burst profile. The physical reason for the temporary stalling of the front is still uncertain, although Bhattacharyya & Strohmayer (2005a) suggested that it might be caused by the accretion-induced pole-ward motion of burning shell matter.

The proposed model of Bhattacharyya & Strohmayer (2005a) suggests that the non-PRE double-peaked bursts can be a useful tool to understand thermonuclear flame spreading on neutron star surfaces. Such an understanding may be important to constrain stellar surface parameters, as well as to model burst oscillations and their frequency evolution during burst rise (Bhattacharyya & Strohmayer 2005b; 2005c). Accurate modeling of burst oscillations has importance for constraining neutron star masses and radii, and hence the dense matter equation of state (EOS) (Bhattacharyya et al. 2005). However, the prospect of using such bursts as a tool for these purposes depends on the validity of the Bhattacharyya & Strohmayer (2005a) model. In this Letter, we report the discovery of oscillations for the first time from a non-PRE double-peaked burst, analysing RXTE PCA data from the LMXB 4U 1636-536, and show that this model can qualitatively and simultaneously explain the observed burst profile, spectral evolution, and oscillation amplitude. Our study also indicates how oscillations during a non-PRE double-peaked burst can be very useful to constrain

the size and  $\theta$ -position of the burning region, and hence to constrain other parameters unambiguously.

## 2. Data Analysis and Results

We analyze the RXTE PCA archival data of a double-peaked burst (Date of observation: Feb 28, 2002; ObsId: 60032-05-15-00) from 4U 1636–536. The height of the second peak ( $\sim 5000$  counts/s/PCU) is approximately three times larger than that of the first peak (Fig. 1). This burst is weaker than PRE bursts observed from this source, which typically have  $\sim 7000$  counts/s/PCU (Strohmayer et al. 1998). The similarity of burst profiles in different energy bands also shows that this is not a PRE burst.

We discovered oscillations (with frequency close to the stellar spin frequency  $\sim 582$  Hz; Strohmayer & Markwardt 2002) during the first intensity peak, but not during the second. We calculated the power spectrum of 1 s of data during the first peak (see inset panel of Fig. 1). At 2 Hz resolution we find a peak power of 13.4 at the frequency  $\sim 581$  Hz. The probability of obtaining a power this high in a single trial from the expected  $\chi^2$  noise distribution (4 dof) is  $\approx 2.18 \times 10^{-5}$ . As the oscillations have been searched at the known frequency, and burst oscillation frequency in 4U 1636–536 does not evolve by more than  $\approx 3$  Hz (Giles et al. 2002; Munro et al. 2002; Bhattacharyya & Strohmayer 2005b), multiplying by the number ( $= 3$ ) of trials, we get a significance of  $6.55 \times 10^{-5}$ , which implies a  $\sim 4\sigma$  detection. We also fit the phase-folded lightcurve of 1 s of data (marked by the vertical dashed lines in Fig. 1) with a combined model of a sinusoid and a constant, and find that the rms amplitude of the oscillations is  $0.082 \pm 0.022$ .

In order to track the spectral evolution during the burst, we break the burst profile into smaller time bins, and for each bin perform spectral fitting using a single temperature blackbody model (bbodyrad in XSPEC), as generally burst spectra are well fit by a blackbody (Strohmayer & Bildsten 2003). During the fitting, we fix the hydrogen column density  $N_H$  at a value  $0.56 \times 10^{22} \text{ cm}^{-2}$  (Bhattacharyya & Strohmayer 2005a). The fitting is performed after subtracting the persistent (i.e., preburst) emission from the emission during the burst. We show the time evolution of the best fit values of temperature and radius (calculated from the bbodyrad “normalization” parameter) in the panels *b* & *c* of Fig. 2. This figure shows that these parameters are well correlated with the intensity profile (panel *a*, Fig. 2), and the radius, which is a measure of the source emitting area, increases with time in a manner indicative of flame spreading. The lack of an increase in radius correlated with the drop of temperature also shows that this is not a PRE burst. Note that the reduced  $\chi^2$  values for some of the time bins are high ( $> 1.5$  for two out of 14 bins). Bhattacharyya & Strohmayer

(2005a) argued that this is because of different temperature values at different locations in the burning region at a given instant.

The persistent emission may vary during the burst, which can have some effect on the inferred radius values derived from spectral fitting. To explore this possibility, we fit the preburst emission with a cut-off power law model (cutoffpl in XSPEC), after subtracting the PCA background (estimated using the FTOOL pcabackest in the standard manner). Then we fit the background subtracted burst spectra with the combined blackbody and cut-off power law models. During this procedure, we fixed the photon index and high energy cut-off parameters of the cut-off power law model to the best fit values for the preburst emission, but we let the normalization parameter vary. The resulting temporal evolution of blackbody temperature and radius were found to be very similar to those shown in Fig. 2, providing confidence in the evolutionary tracks shown in panels *b* & *c* of this figure. This also shows that the source emission area actually increases as the burst progresses.

### 3. Model Calculations

Here we use a model that is very similar to the model proposed by Bhattacharyya & Strohmayer (2005a), except here we consider ignition at high latitudes (instead of polar ignition) in order to accommodate the observed oscillations during the first intensity peak. For the stellar parameter values and the observer's inclination angle ( $\theta = i = 40^\circ$ ) mentioned in Fig. 3, we find that a hotspot at  $\theta = 10^\circ$  with  $\theta$ -width  $10^\circ$  and  $\phi$ -width  $60^\circ$  gives a rms amplitude of brightness oscillations equal to 0.085, which is consistent with the observed value (see § 2). Here  $\theta$  and  $\phi$  are the polar angle and the azimuthal angle respectively. Therefore, we assume that the ignition starts at  $\theta = \theta_c = 10^\circ$  (for  $i = 40^\circ$ , and the same stellar parameter values) in a narrow  $\phi$ -symmetric belt. We use this simple assumption, because (1) a rigorous theoretical calculation of thermonuclear flame spreading considering all the main physical effects (e.g., those mentioned in Bhattacharyya & Strohmayer 2005b; 2005c) is not available at the present time (but see Spitkovsky, Levin, & Ushomirsky 2002), and (2) we wish to check whether our simple model can explain the salient features of the double-peaked bursts, before using a more complex model. According to our model, the narrow belt at  $\theta = \theta_c$  expands in both directions with an angular speed  $\dot{\theta}(\theta) = F(\theta)$ , where  $F(\theta) = 1/(t_{\text{total}} \times \cos \theta)$  for  $\theta \leq 90^\circ$ , and  $F(\theta) = 1/(t_{\text{total}} \times \cos(180^\circ - \theta))$  for  $\theta \geq 90^\circ$ . Here  $t_{\text{total}}$  is the time needed by the front to propagate from a pole to the equator in the absence of any stalling. Note that we adopt this expression of  $F(\theta)$  from Spitkovsky et al. (2002), but our qualitative results depend mainly on the temporary front stalling, and not on this particular expression. We assume that the stalling of the front happens between the

polar angles  $\theta_1$  and  $\theta_2$  (with  $\theta_1 < \theta_2 < 90^\circ$ ):  $\dot{\theta}(\theta)$  decreases linearly from  $\theta = \theta_1$  to  $\theta = \theta_m$ , reaching a value  $s/t_{\text{total}}$ , and then increases linearly up to  $\theta = \theta_2$  reaching a value  $F(\theta_2)$ . Between  $\theta = \theta_2$  and  $\theta = 180^\circ$ , we assume  $\dot{\theta}(\theta) = F(\theta)$ . To calculate the temperature of a given location at a certain time, we assume that after ignition of the fuel at that location, the temperature increases from  $T_{\text{low}}$  to  $(T_{\text{low}} + (0.99 \times (T_{\text{high}} - T_{\text{low}})))$  following the equation  $T(t) = T_{\text{low}} + (T_{\text{high}} - T_{\text{low}}) \times (1 - \exp(-t/t_{\text{rise}}))$ , and then decays exponentially with an e-folding time  $t_{\text{decay}}$ . We compute lightcurves and spectra using this model (see Bhattacharyya & Strohmayer 2005a for more details). In our calculations, we consider the Doppler, special relativistic, and general relativistic (gravitational redshift and light-bending in Schwarzschild spacetime) effects.

In Fig. 3, for an example set of source parameter values, we show the evolutionary tracks of model intensity and spectral parameters (blackbody temperature and radius) that qualitatively match the observed features of the double-peaked burst (Fig. 2). For example, the model intensity profile reproduces the  $\sim 1/3$  ratio of first peak height to second peak height of the observed burst, as well as the general shape of the observed profile. For both data and model, the blackbody temperature starts from a high value, decreases up to the time when the intensity becomes minimum between two peaks, increases up to the time when the intensity reaches the second peak, and declines after that. The inferred radius for both data and model starts from a low value, increases up to the time when the intensity reaches the first peak, remains almost unchanged up to the time when the intensity becomes minimum between the two peaks, increases again up to the time when the intensity reaches the second peak, and remains almost unchanged after that. The almost constant value of the inferred model radius during the decline of the first intensity peak (marked by the two vertical lines in Fig. 3) is due to the temporary stalling of the burning front. The clear occurrence of the same feature during the observed burst (see Fig. 2) is therefore a strong indication of the slowing down of the burning front, and is supportive of our model.

We note that the peaks of the model burst rise more gradually than those of the observed burst. As Bhattacharyya & Strohmayer (2005a) noted, this may be because of the delay between ignition at depth and emergence of the radiation. The observed temperature during the second intensity peak is probably slightly higher than the initial temperature (Fig. 2), while this does not happen for the model. One possible reason for this is, during the second intensity peak the burst peak temperature ( $T_{\text{high}}$ ) may be slightly higher than that just after the burst onset, while in the model we consider the same value of  $T_{\text{high}}$  for the whole stellar surface. Such a temperature difference is not unrealistic, as in the case of accretion via a disk, the lighter element hydrogen is expected to spread more towards the pole than, for example, helium. This would cause a higher hydrogen-to-helium ratio near the pole (than near the equator), and hence lower  $T_{\text{high}}$  value just after the burst onset (as the burst ignites

at a high latitude). We also note that the total duration of the model burst scales with the parameter  $t_{\text{total}}$  (see first paragraph of this section), and hence can be adjusted by changing the value of this parameter.

#### 4. Discussion and Conclusions

In this Letter we show that our simple model, based on thermonuclear flame spreading and its temporary stalling, can qualitatively reproduce the intensity and spectral profiles of the observed double-peaked burst. Moreover, the data show a strong signature of temporary burning front stalling, that matches well with our model (see the time intervals marked by two vertical lines in Figs. 2 & 3). These strongly suggest that non-PRE double-peaked bursts are caused by the propagation of the thermonuclear burning front and its temporary stalling. Our model can also explain the rarity of these bursts (see Bhattacharyya & Strohmayer 2005a; Bhattacharyya et al. 2000).

Our discovery of millisecond period brightness oscillations from the observed burst is the first such observation from a non-PRE double-peaked burst, and our model (with the parameter values that qualitatively reproduce the observed intensity and spectral profiles) can account for the observed rms amplitude. The oscillations are seen during the first intensity peak, but not the second. Our model accounts for this in the following way. After the burst has ignited at a high latitude, the initially small hotspot produces the brightness oscillations due to stellar spin. As the burning front propagates towards the equator, its  $\theta$ -ward motion stalls temporarily, and its  $\phi$ -ward motion quickly gives the burning region the shape of a  $\phi$ -symmetric belt. After a few seconds, as its  $\theta$ -ward motion resumes, this  $\phi$ -symmetric belt expands into the opposite hemisphere, and hence no oscillations occur during the second intensity peak. The temporary stalling of the  $\theta$ -ward motion, but not of the  $\phi$ -ward motion, is consistent with the suggestion made by Bhattacharyya & Strohmayer (2005a), that this stalling is caused by accretion-induced pole-ward motion of burning shell matter, while the accretion is conducted via a disk, and hence is  $\phi$ -symmetric.

In the present study, for given stellar parameter values and observer's inclination angle, the observed rms amplitude of oscillations provides the location and size of the burning region. Therefore, we suggest that, the observation of stronger oscillations (preferably with frequency evolution) during a non-PRE double-peaked burst can provide an important additional tool to understand thermonuclear flame spreading.

To more firmly establish our model, as well as to understand the physics behind front stalling, it is now essential to conduct rigorous fluid dynamical calculations and simulations,

considering all the main physical effects that appear during thermonuclear flame spreading on rotating neutron star surfaces. It is also important to expand the sample of non-PRE double-peaked bursts by observing 4U 1636-536, and other similar sources for longer time periods with RXTE PCA and future larger area detectors.

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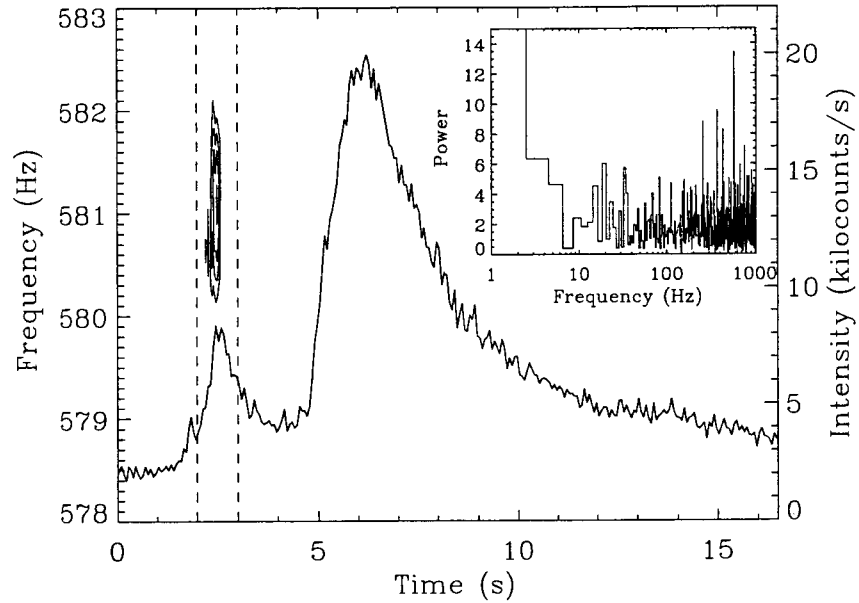


Fig. 1.— A non-PRE double-peaked burst from 4U 1636-536. The main panel shows the PCA count rate profile (four PCUs on). The inset panel shows the power spectrum of the 1 s interval (marked with vertical dashed lines in the main panel) during the first peak, rebinned to 2 Hz resolution. The peak near 581 Hz implies a significant signal power. Power contours using the dynamic power spectra (for 0.5 s duration at 0.03 s intervals) are shown in the main panel (Strohmayer & Markwardt 1999). Contour levels 15, 18, 21, 25 of power are given. These power contours show that oscillations occur only during the first intensity peak.

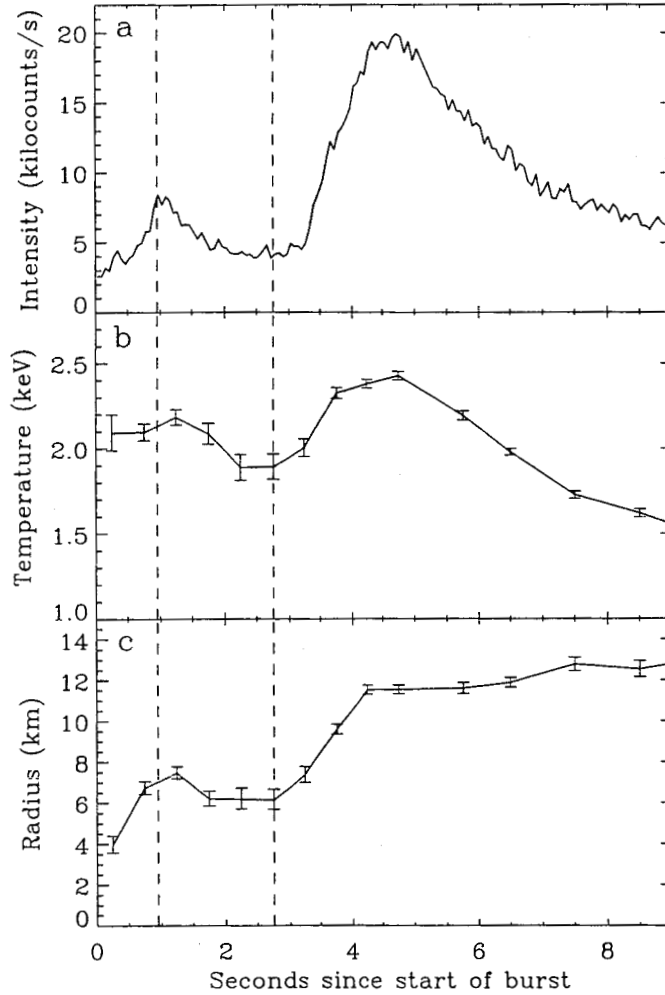


Fig. 2.— A non-PRE double-peaked burst from 4U 1636–536. Panel *a* gives the bolometric burst profile. Panels *b* & *c* show the time evolution of the blackbody temperature and the apparent radius (assuming 10 kpc source distance) of the emission area respectively, obtained by fitting the burst spectrum (persistent emission subtracted) with a single temperature blackbody model. The error bars are  $1\sigma$ . Vertical dashed lines give the time interval in which the radius (and hence the source emission area) does not change, and the possible burning front stalling occurs.

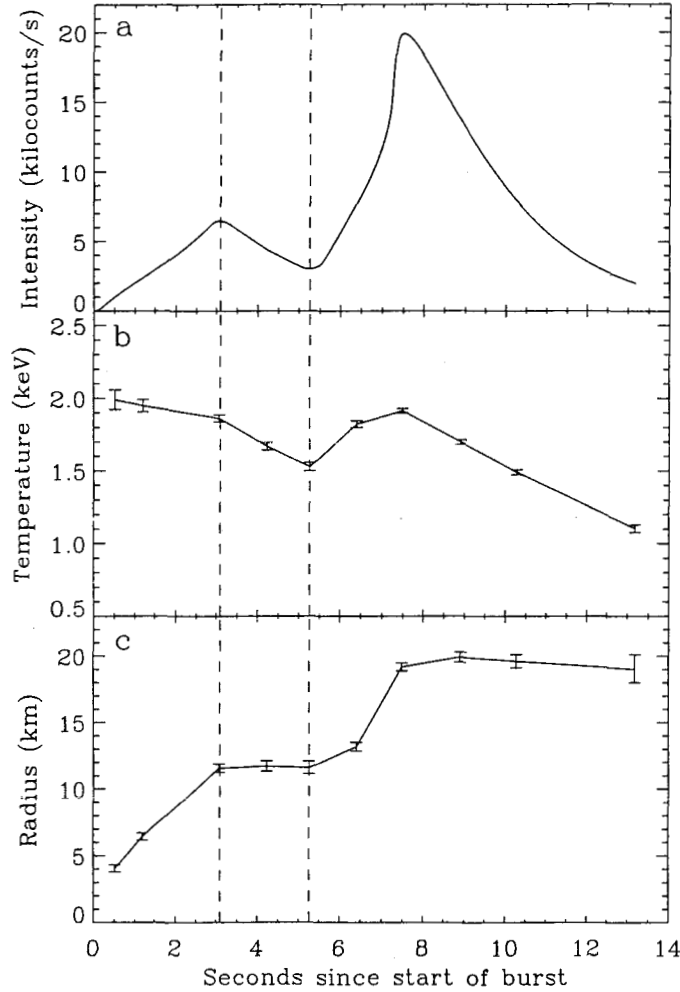


Fig. 3.— Model (convolved with a PCA response matrix) of double-peaked bursts: for all the panels, the burst is normalised so that its second intensity peak has the same count rate as that of the second peak of the observed burst. Panels are similar to those of Fig. 2. Model parameter values are the following: stellar mass  $M = 1.5M_{\odot}$ , dimensionless stellar radius to mass ratio  $R/M = 5.5$ , stellar spin frequency  $\nu_{*} = 582$  Hz, observer’s inclination angle  $i = 40^{\circ}$ ,  $\theta_c = 10^{\circ}$ ,  $\theta_1 = 40^{\circ}$ ,  $\theta_m = 43^{\circ}$ ,  $\theta_2 = 46^{\circ}$ ,  $s = 0.004$ ,  $t_{\text{total}} = 6$  s,  $t_{\text{rise}} = 0.05$  s,  $t_{\text{decay}} = 8$  s,  $T_{\text{low}} = 0.2$  keV, and  $T_{\text{high}} = 2.6$  keV (see text for the definitions of the parameters). The error bars are of  $1\sigma$  size. Vertical dashed lines give the time interval, in which radius (and hence the source emission area) does not change much, and the burning front stalling occurs.